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THE USE OF CFD MODELLING AS A TOOL FOR SOLVING MINING HEALTH AND SAFETY PROBLEMS

Ting Ren¹ and Rao Balusu²

ABSTRACT: Many safety and health problems in the coal mining industry involve the understanding and analysis of the mechanism of fluid or gas flow, including goaf gas migration, face ventilation and dust dispersion. Computational Fluid Dynamics or CFD has become a powerful tool to assist mining engineers and find solutions to these problems. The use of CFD modelling in goaf gas management and drainage, goaf inertisation for heating control, and longwall dust control strategies is summarised.

CFD MODELLING

CFD is commonly accepted as the broad topic embracing mathematics and numerical solution, by computational methods, of the governing equations which describe the motion of fluid flow, the set of the Navier-Stokes equations, continuity and any additional conservation equations, such as energy or species concentrations. Today CFD become a powerful tool in almost every branch of fluid dynamics and engineering.

CFD modelling has been used in the mining industry in a number of areas, including control of methane and spontaneous heating (Creedy and Clarke, 1992; Tauziède *et al* 1993; Ren and Edwards, 2000), dust control (Aziz *et al*, 1993; Sullivan *et al*, 1993), mine fires and explosions (Lee, 1994), auxiliary ventilation layouts in rapid heading development (Moloney *et al*, 1998). More recently, CFD codes are being used in Australia for development of goaf gas control (Balusu *et al*, 2002, 2004) and goaf inertisation strategies (Balusu *et al*, 2002, 2005), dust control on longwalls (Ren and Balusu, 2005; 2007; 2009), heating gases dispersion in the goaf (Ren and Balusu 2008) and goaf heating simulations (Yuan and Smith, 2008).

The development of CFD models involves a number of complex steps, depending upon the specific problems to be addressed. The most important step is to understand the issues to be investigated, the engineering concepts and the results to be expected from the modelling studies. For mining related health and safety problems such as gas management, this would typically require visits to the mine site to discuss the problem with the ventilation engineers and examine relevant data to clarify any technical issues before developing the CFD models. In summary, the following steps would be involved in the process of any CFD models:

- Field studies to obtain fundamental data and information – this would typically involve the collation of mine design plans, ventilation layout and gas monitoring data, gas drainage systems, geological and geotechnical reports, depending on the problems to be studied;
- Construction of CFD model geometry and computational mesh/grid – The raw data collected from the field studies has to be simplified to produce the model geometry and grid (2D or 3D) which has to be conceptually sophisticated enough to represent the real case to be investigated. This is typically done by the use of a CAD style mesh generator or pre-processor of a CFD package;
- Setup of CFD model – The above computational mesh will be brought into the CFD processor or the solver for the definition of computational models, boundary conditions, flow properties and other functions that need to be performed by user defined programs or functions (UDF); This step may also involve the refinement of meshing, mesh quality and boundary checking, and in some case, the complete re-meshing of the initial model;
- Initial model simulations – Once the CFD model setup has been completed, an initial run of the CFD model with a few iterations is often performed to check the stability and convergence of the model. 'Engineering judgement' is needed at this stage to examine if the model is producing meaningful results. In many cases, modifications are needed to modify boundary

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conditions, computational models, UDF functions and mesh improvements. A good base-model should be characteristic of good convergence and meaningful results independent of computational mesh;

- Base-model simulation and validation using field or experimental data – The above base-model needs to be calibrated and validated against real data, typically ventilation survey data or gas monitoring data. The base model will be fine-tuned to produce results that show reasonable good agreement with the real case;
- Parametric studies to investigate various 'what if' scenarios of the problems and solutions – The fine-tuned base model can now be used to carry out a wide range of parametric or sensitivity studies to investigate the problems when changing one or two design parameters and develop solutions or optimum strategies.
- Figure 1 shows the CFD model geometry and computational grid of a longwall panel using perimeter ventilation system.

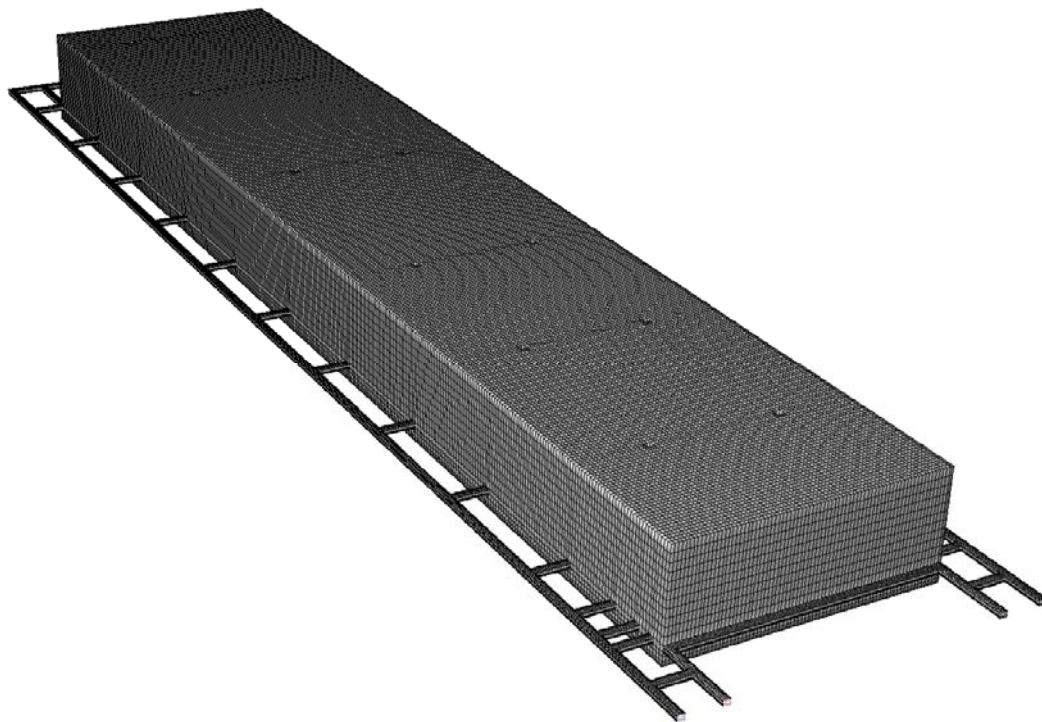


Figure 1 - CFD model geometry and computational grid of a longwall panel

GOAF GAS MANAGEMENT AND DRAINAGE

The fundamental understanding of goaf gas migration characteristics is important for modern longwalls with high gas emission, and in seams liable to spontaneous heating. Knowledge of the impacts of various operational and geological factors on the accumulation of goaf gas in the goaf is essential for the design of effective goaf gas management and gas drainage system to reduce fugitive gas (mainly methane) reporting to longwall and return ventilation. Figure 2 shows the goaf gas distribution patterns for an Australian longwall panel using perimeter ventilation. The face is ventilated with around 80 m³/s of airflow, with goaf gas emissions between 1 500 L/s and 2 000 L/s consisting of 65% carbon dioxide (CO₂) and 35% methane (CH₄). The model results indicate that a gas-rich zone of high concentration goaf gas (CO₂ and CH₄) starts to accumulate close to the TG side of the goaf at about 100 m behind the face and at lower level of the goaf due to the heavy goaf gas (mainly CO₂). The modelling results also indicate that oxygen ingress into the goaf can be up to 400 m behind the face on intake side of the goaf. Oxygen levels in the vicinity of the goaf perimeter road are in the range of 5 to 10%, and oxygen tends to layer towards the top of the goaf as a result of the heavier goaf gas.

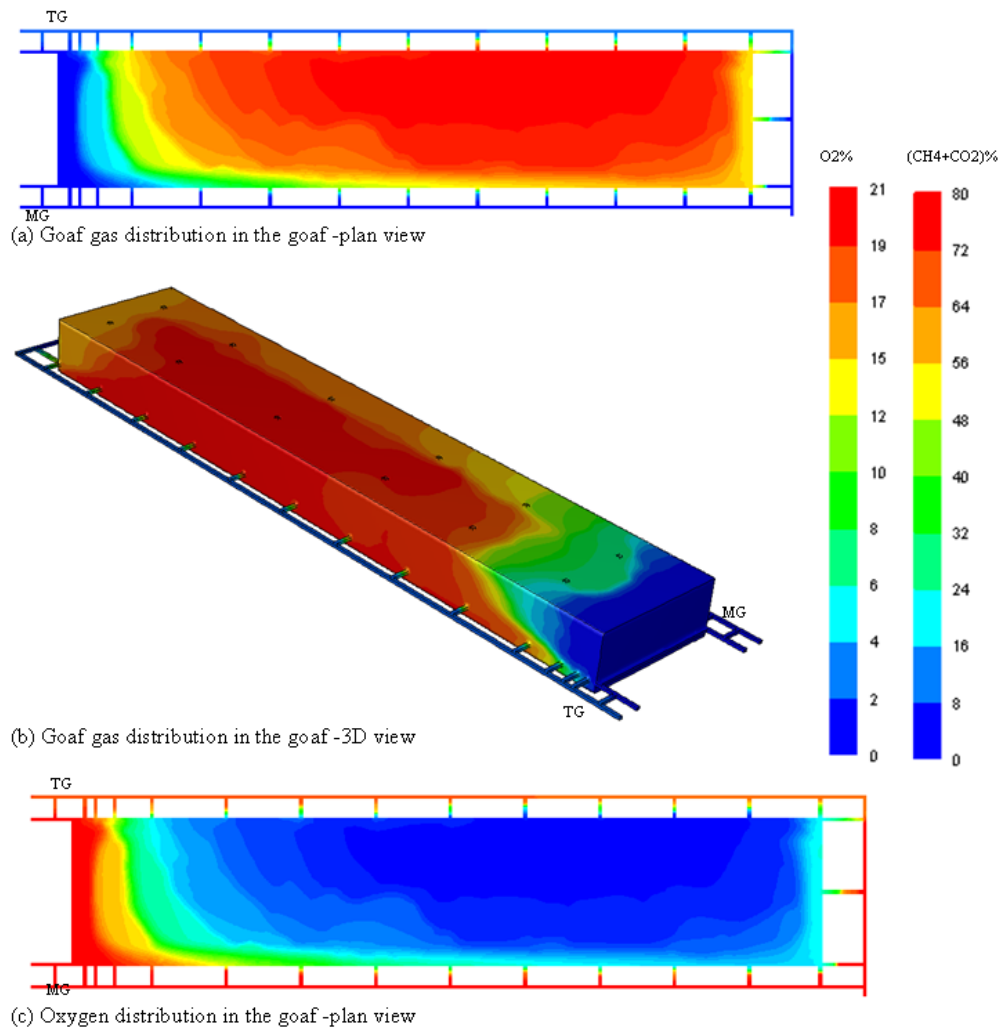


Figure 2 - CFD modelling of goaf gas distribution in longwall goaf

In addition to the use of perimeter ventilation system, goaf gas drainage is needed to reduce goaf gas reporting to the longwall and return ventilation resulting from high goaf emissions. Figure 3 shows the use of surface goaf wells for goaf gas drainage. Modelling results show that the strategy of goaf gas drainage from goaf holes near the face in combination with continuous gas drainage from deep holes would substantially improve the overall performance of the gas drainage system and reduces tailgate gas concentrations. Depending upon the geological conditions in the panel, these holes should be located at about 50 m from the rib and close enough to the seam level in elevation to avoid air ingress and maximise the capture of high concentration CO_2 gas.

Modelling study and field application experiences demonstrated that the optimum goaf gas drainage strategy should include the following:

- Goaf holes should be drilled ahead of mining on return side of the goaf, preferably at 30 to 70 m from gateroad depending on the longwall caving conditions, and at 100 to 300 m spacing depending on the goaf gas emissions and other conditions,
- Goaf holes diameter should be in the range of 250 mm to 400 mm and cased using both competent and slotted steel pipe according to strata and predicted caving conditions to improve borehole stability and maximum gas capture,
- Borehole bottom elevation should be adjusted according to the goaf gas compositions. Goaf hole should be drilled close the seam if the goaf holes aimed to drain heavier goaf gas such as CO_2 in the goaf,

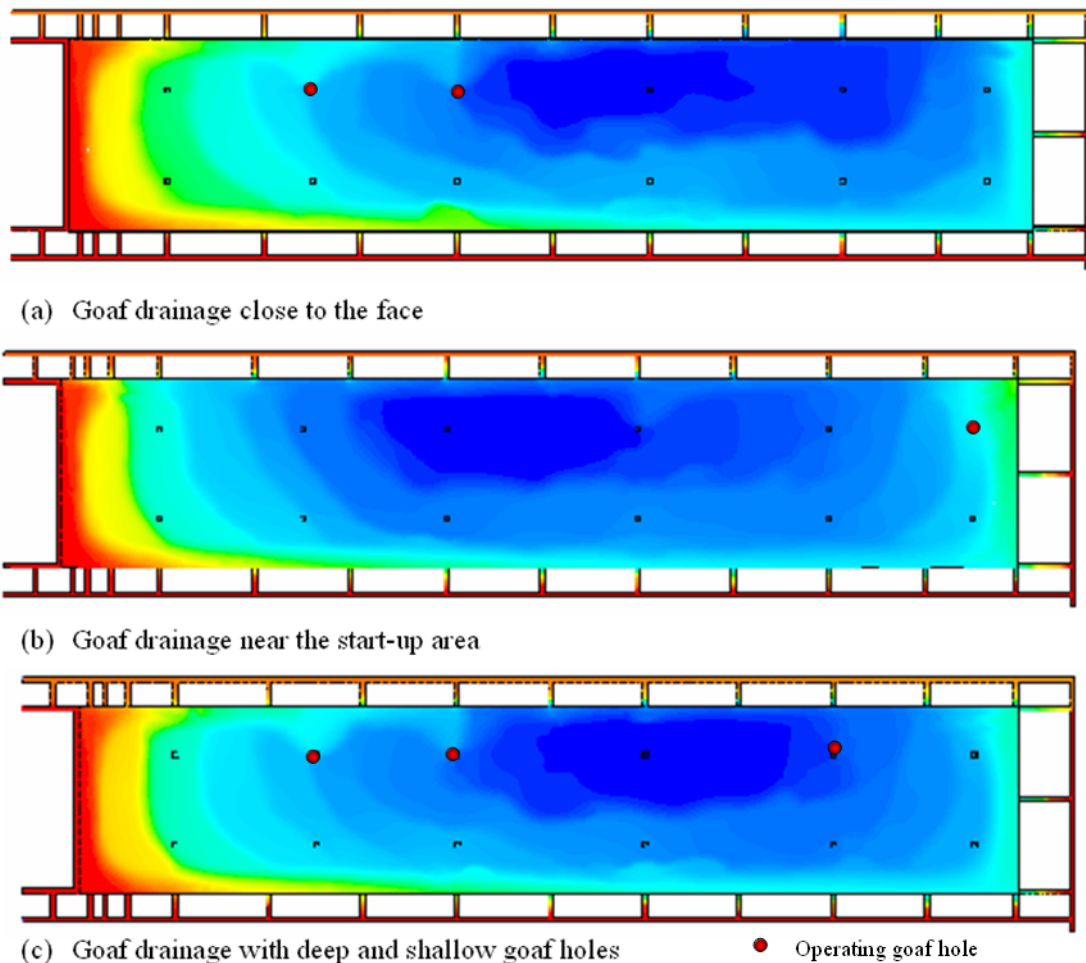
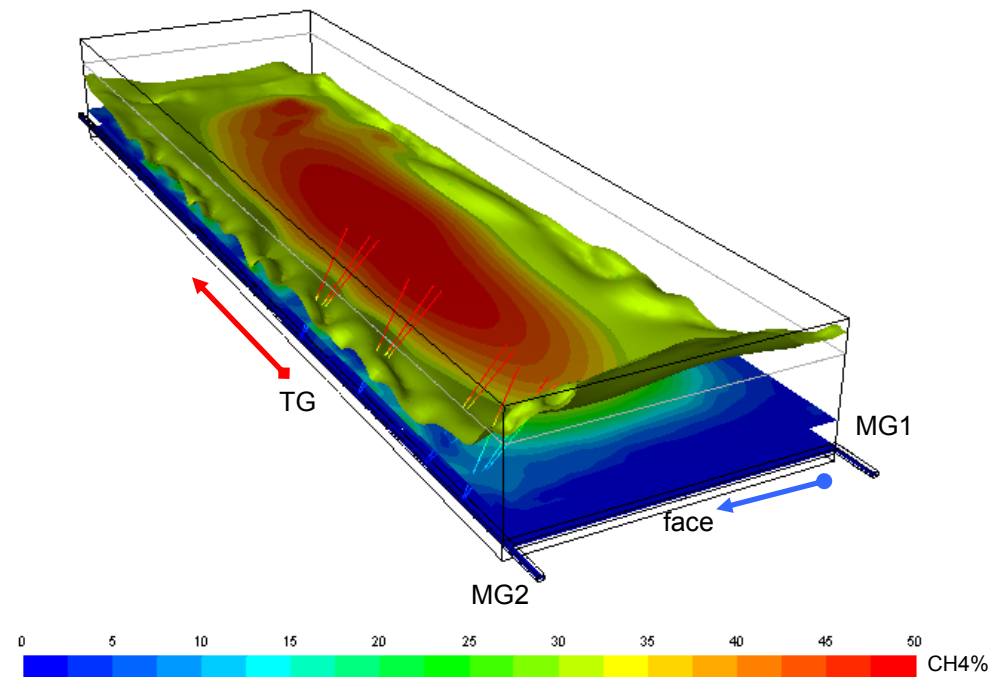


Figure 3 - Modelling of goaf hole drainage optimisation

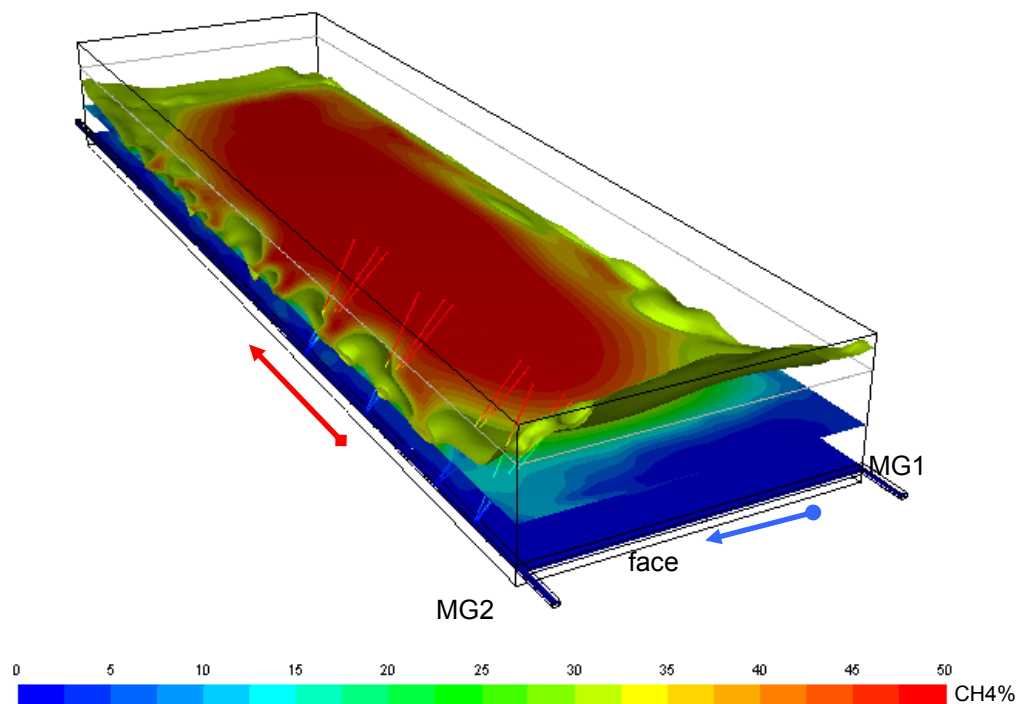
- Total capacity of the goaf gas drainage plants should be around 2 to 3 times the expected goaf gas emissions in the panel to achieve optimum performance of the gas drainage system and provide better gas control on the face,
- Goaf gas drainage should include a combination of goaf holes near the face and deep goaf holes in the panel in order to improve the overall gas drainage efficiency and to reduce the effects of barometric pressure changes on tailgate gas levels,
- The strategy of continuous operation of deep goaf holes at moderate capacity should be implemented. i.e., intermittent operation of deep goaf holes at high capacity may not improve the overall efficiency and may lead to problems,
- Ventilation system in the panel should be designed to minimise oxygen ingress into the goaf, including immediate sealing-off all the cut-throughs behind the face, in order to improve overall gas drainage efficiency,
- Oxygen concentration at all goaf holes should be continuously monitored and controlled at less than 5% to reduce the risk of spontaneous heating in the longwall goafs,
- Goaf gas drainage should be carried out from more goaf holes at optimum capacity. It is preferable that gas drainage is carried out by 3 to 4 holes, rather than 1 to 2 holes, this would reduce oxygen ingress into the goaf.

In combination with field trials, the CFD modelling results have been used to design the goaf hole parameters and the development of optimum goaf gas management and drainage strategies. Significant improvements in goaf gas capture have been achieved in several coal mines in Australia (Balusu *et al*, 2002; 2004).

CFD modelling has been used to optimize the design of roof boreholes and overlying gas drainage road in Chinese coal mines using 'Y' ventilation system (a bleeder road between a retaining wall in the goaf and solid coal rib). Figure 4 shows the CFD modelling results of roof boreholes drilled at different angles to intercept seam gas from overlying seams. Results show that boreholes drilled at $65^{\circ}\sim 70^{\circ}$ are more effective to intercept high concentration goaf gas than boreholes at $45^{\circ}\sim 50^{\circ}$, and it is equally important to case the boreholes up to 30 m and maintain borehole operation beyond 200 m behind the face.



(a) Roof boreholes intercepting high methane gas at 30m above roof



(b) Roof boreholes intercepting high methane gas at 40m above roof

Figure 4 - CFD modelling of roof boreholes intercepting seam gas from overlying seams

SPONTANEOUS HEATING AND GOAF INERTISATION

A number of heating incidents have occurred in recent years leading to major production losses and safety risk for a number of mines in Australia. The coal seams in these mines areas are generally thick, and the risk of goaf heatings increase significantly due to the large quantities of broken coal left behind the chocks and its exposure to deep oxygen penetration in the goaf due to increased ventilation volumes. A snapshot of the typical goaf gas distribution behind the longwall face using perimeter road is presented in Figure 5. Gas monitoring results show that intake air ingress on the MG side of the panel was high, with the oxygen level at more than 17% even at 400 m behind the face. Even on the TG side, oxygen ingress appears to extend up to 100 m behind the face. High oxygen penetration around the start-up area can also be observed. This high oxygen ingress could lead to heating development in the goaf, particularly during face stoppage or slow face retreat in the panel.

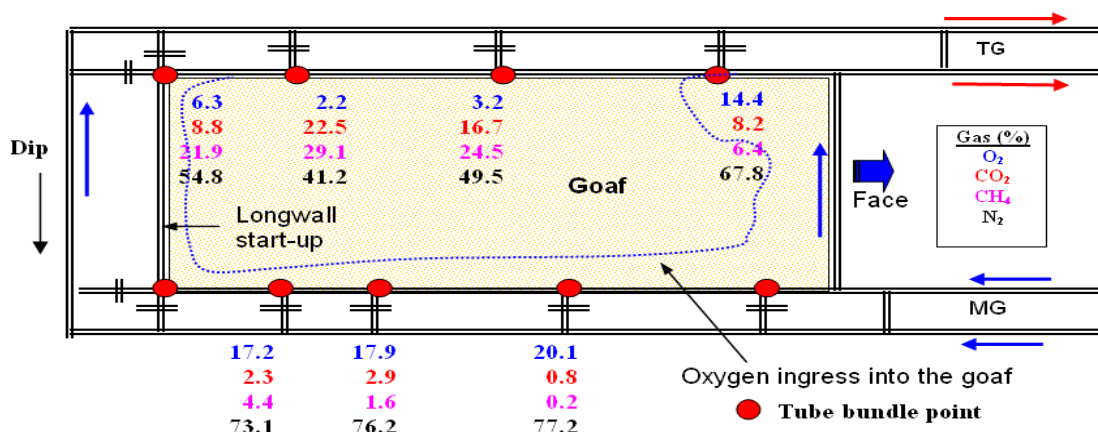


Figure 5 - Typical gas distribution in a longwall goaf

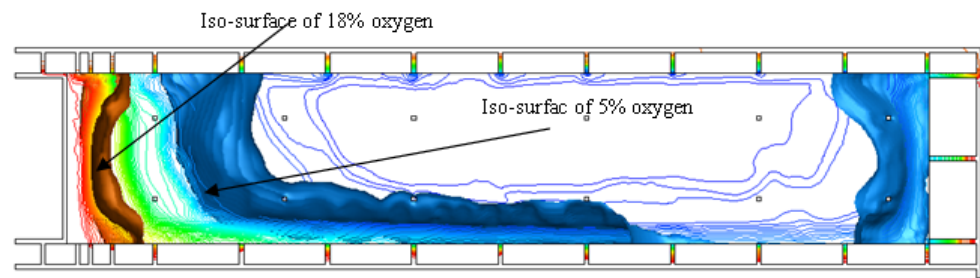
CFD modelling was used to investigate oxygen ingress into the goaf and identify 'oxidation zones' where spontaneous heating of coal is most likely to take place. Figure 6 shows the CFD modelling results of oxygen penetration pattern into the goaf and the mapping of 'oxidation zones' (with oxygen concentration between 5~18%) in the goaf using iso-surface of oxygen concentrations. Results show that goaf heating is likely to occur in goaf areas at about 50~200 m behind the face, along the goaf edge of MG side, and in the vicinity of face start-up line.

To minimize the risk of goaf heating, a common practice in Australian longwall mines is to inject inert gas such as nitrogen behind the face to reduce the spatial areas of 'oxidation zones' thus suppress the onset of potential heatings. CFD modelling was used to identify inert gas injection strategies behind the face to achieve the most effective goaf inertisation. Figure 7 shows the effect of inert gas injection at different locations behind the face. Results show that inert gas injection at a location immediately behind the face line will only have negligible impact on goaf inertisation, as most of the inert gas injected will simply disperse into the main ventilation stream and disappear into the return airflow. Even at some 60m behind the face line, the injection of inert gas at a rate of 0.5 m³/s would only have marginal effect on goaf inertisation. CFD results indicate that the most optimum injection locations for the modelled cases should be within the range of 150-400 m behind the face line on the maingate side. The results indicated that inert gas flow rate of 0.5 m³/s would be required for most cases, although in some cases lower flow rates might be sufficient or in some other cases higher flow rates might be required to achieve the desired effect.

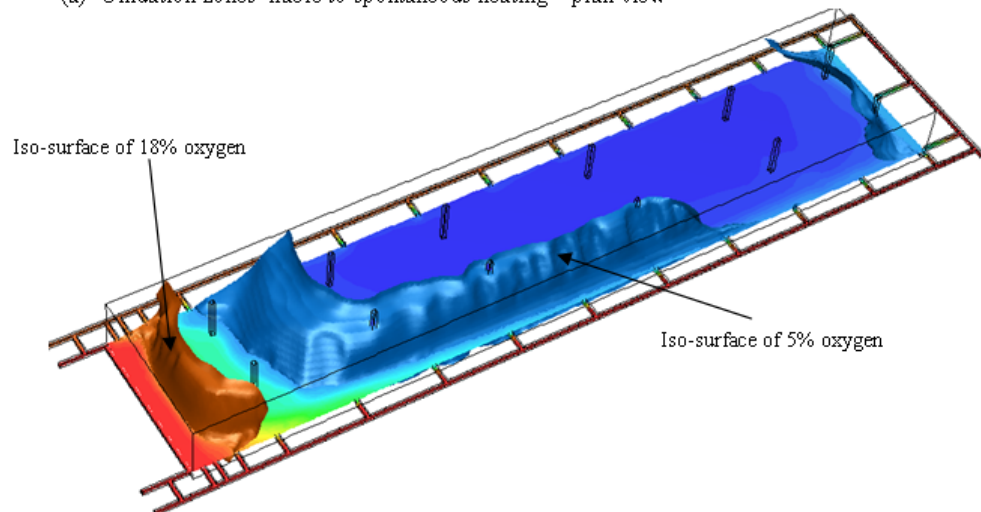
In case of access problems in underground workings, such as after evacuation of personnel from underground workings, the only possible means of goaf inertisation may be via surface drilled boreholes or those existing surface goaf holes for goaf gas drainage. CFD simulations results indicate that an improved goaf inertisation effect could be achieved by injecting inert gas via surface boreholes. By injecting inert gas on both side of the goaf via surface goaf holes would produce a better inertisation result than simply injecting inert gas on one side of the goaf. Similarly it is also important to understand goaf gas distribution patterns so that the correct injection locations can be identified to achieve the maximum goaf inertisation effectiveness.

The main findings from CFD modelling have been implemented in field applications and excellent goaf

inertisation results have been achieved, including longwalls in Australia and Blasting Gallery (BG) panels in India.



(a) 'Oxidation zones' liable to spontaneous heating – plan view



(b) 'Oxidation zones' liable to spontaneous heating – 3Dview

Figure 6 - CFD modelling of oxygen ingress and 'oxidation zones' in the goaf

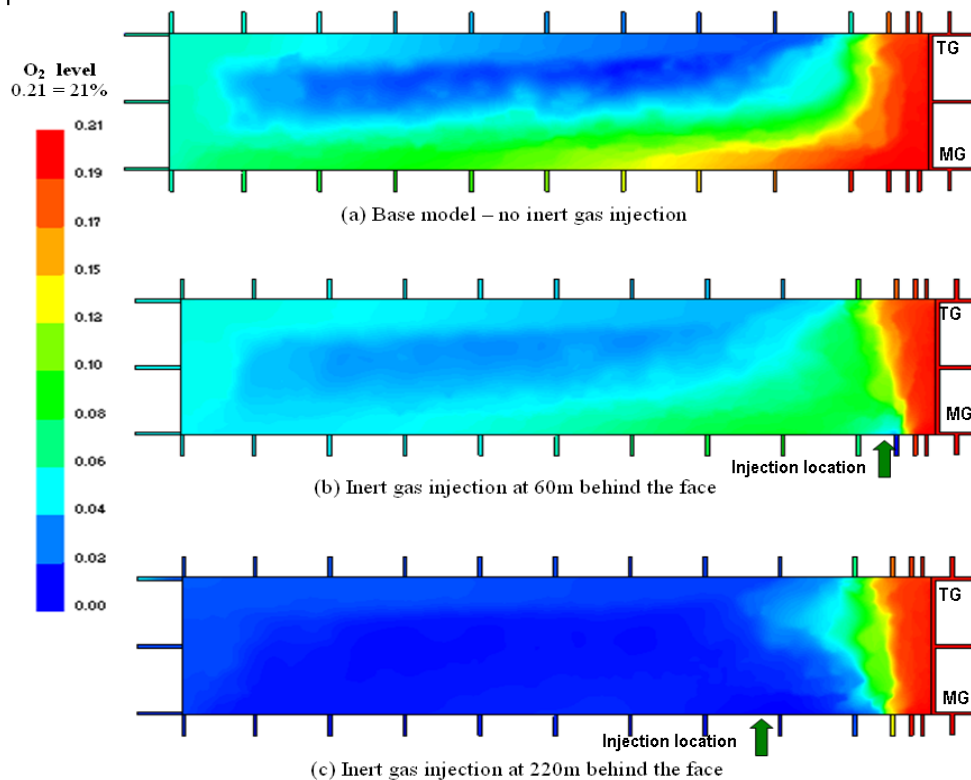


Figure 7 - CFD modelling of goaf inertisation

LONGWALL DUST CONTROL

Management of dust on longwall face is a challenging issue for mine operators, especially for the new generation of longwall faces. The airflow and dust dispersion patterns in a longwall are complex as many factors such as ventilation, cutting machine/chock movements as well as dust control devices (e.g. water sprays and curtains) are involved. Three Dimensional CFD models were built to represent longwall faces in thin, medium and thick seams. Figure 8 shows the layout of the CFD model. These models consist of a section of the full scale coal face and the maingate, and embody the major longwall components such as chocks, shearer, spill plate, BSL/crusher and conveyor. In addition, dust scrubbers, shearer clearer, venturi sprays and curtains were incorporated into the models to investigate the effect of various dust control options.

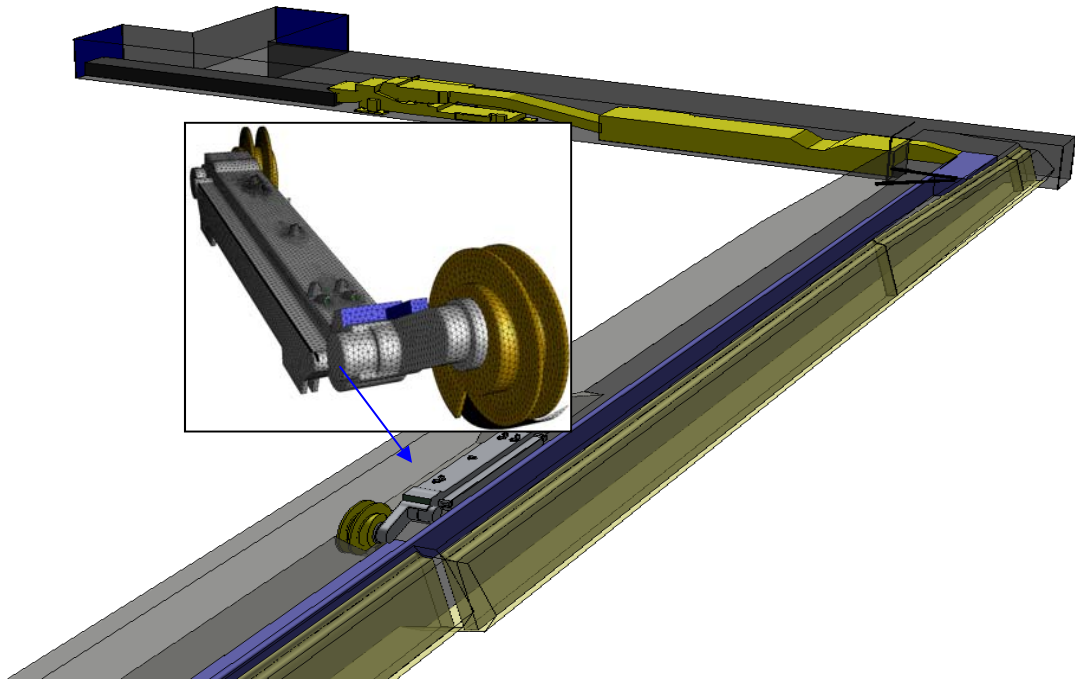
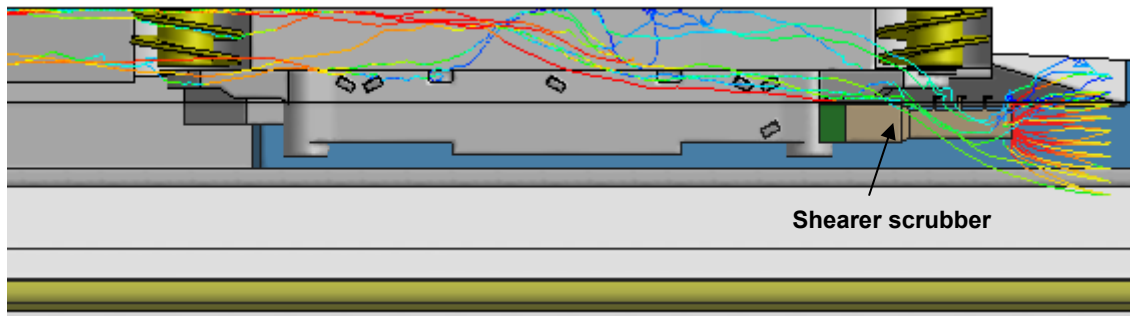


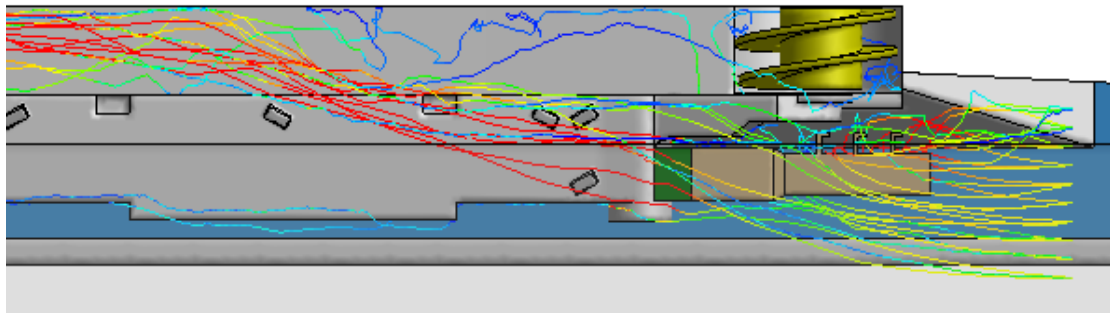
Figure 8 - Layout of the longwall CFD model for dust modelling

To establish the base airflow patterns on the longwall face, CFD simulations were carried out with a range of ventilation rates between 30 m³/s to 80 m³/s. Field information and data were used to establish the geometry and boundary conditions of the longwall faces representing 4.5 m thick seam, 3.0 m medium seam and 2.1 m thin seam. Results from the base-case CFD models were calibrated and validated against field data obtained from three Australian longwalls. The validated models were then used for extensive parametric studies involving changes in air flow rates, shearer Clearer/sprays, the position of scrubbers and curtains etc. These parametric studies can be used to investigate the effect of various controls on dust flow patterns and dust capture on longwall faces.

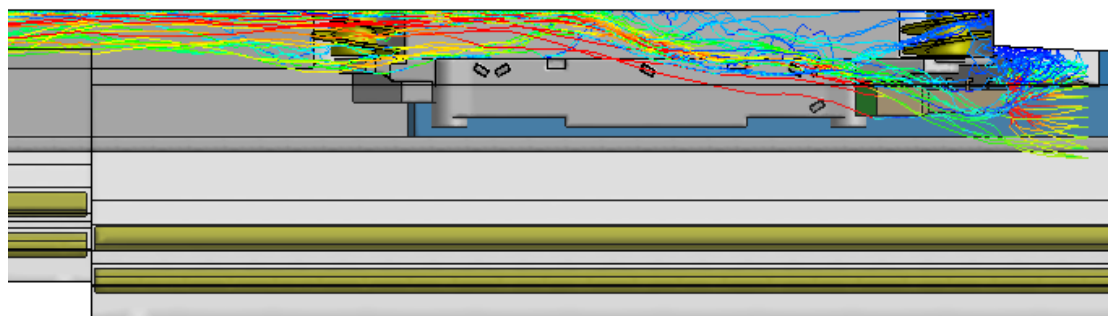
A particular application of CFD modelling has been the development of a new shearer scrubber system. CFD was used as a design tool to optimize parameters including the locations of both inlet and outlet (airflow discharge direction), and the capacity of the scrubber in relation to the face airflow rates. Figure 9 respectively shows the modelling results for the dust scrubber system. Modelling results indicate scrubber inlet located towards face ventilation offers improved advantage of capturing a large portion of the dust particles from roof/chock movements ahead of the shearer as well as some of the dust from the spalling area. This scrubber inlet location is also effective for confining the dust particles from these sources to the face. In practice, this option also has the advantage of maintaining the clearance of the scrubber inlet(s) from the direct falling and stacking of coal lumps from the cutting drum and spalling area. Modelling studies showed that it is important to correctly position the scrubber outlet location and discharge direction to improve the overall diversion of escaped dust particles away from the face walkway. As shown in Figure 9 (c), scrubber outlet discharge tilted slightly towards the face helps the confinement of dust particles to the face and the overall diversion of dust clouds away from the walkway.



(a) Scrubber inlet facing the ventilation direction



(b) Scrubber inlet facing the shearer drum



(c) Scrubber discharge

Figure 9 - CFD modelling of shearer dust scrubber

In collaboration with EnviroCon, CFD modelling results have been used in the design optimisation process for the new shearer dust scrubber system, as shown in Figure 10 (a). The final design included the following key features:

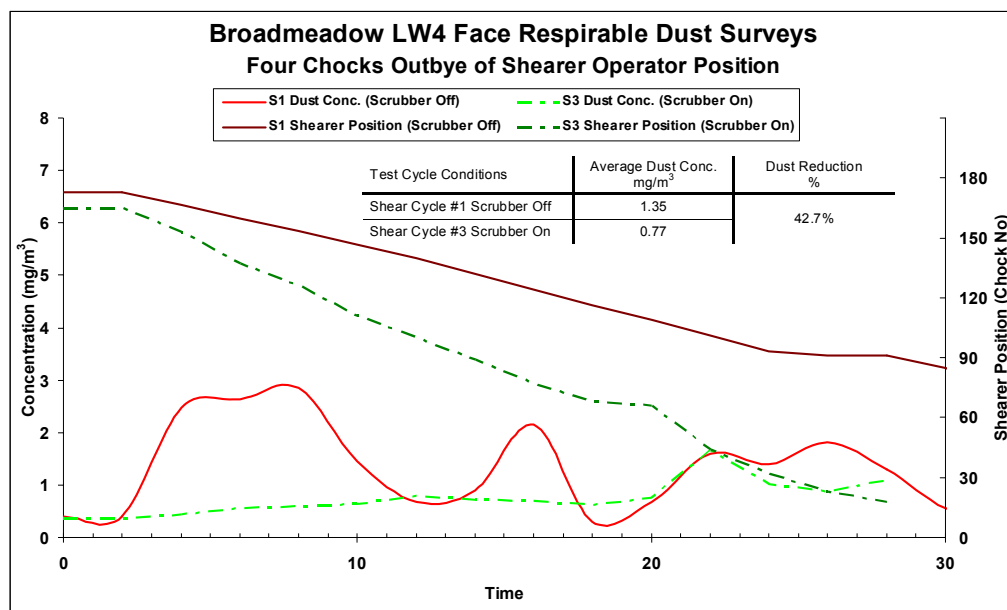
- The scrubber was designed as a compact modular unit to fit the limited space between the ranging arm and the shearer body;
- Scrubber intake duct facing the ventilation direction;
- Fine water sprays embedded into the intake duct to increase scrubber collection area and additional function of 'air curtain' to suppress and streamline dust particles;
- Scrubber exhaust under the ranging arm and tilted 15° towards the face and 45° toward the tailgate.

Field trials of the scrubber system were carried out at BHP Billiton Mitsubishi Alliance's mine at Broadmeadow in Queensland's Bowen Basin. Dust monitoring results indicated that the dust reduction rate varied from 43 per cent (with average dust concentration falling from 1.35 mg/m³ to 0.77 mg/m³) to 56 per cent (with average dust concentration falling from 1.59 mg/m³ to 0.70 mg/m³). Figure 10 (b)

shows the impact of shear scrubber system at 4th Chocks Outbye of Shearer Operator's positions. The results were better than expected and indicated a positive advance in mine safety.



(a) Field trials of shearer dust scrubber system



(b) Impact of shearer dust scrubber system on longwall dust reduction

Figure 10- Field trials of longwall shearer scrubber system and its impact on dust reduction

CONCLUSION

This paper has provided a summary of the application of CFD modelling techniques as a tool for solving mining health and safety problems, including goaf gas management and drainage, goaf heating and inertisation and longwall dust controls. The usefulness of CFD has been demonstrated in the

development of optimum strategies for handling these issues and significant benefits to mine operators both in Australia and overseas such as China and India. CFD modelling results must be validated against field data and engineering judgments, and used as a tool of integrated system combining other computing and experimental methods.

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